

Decadal Trends in Global Pelagic Ocean Chlorophyll: A New Assessment Integrating Multiple Satellites, In Situ Data, and Models

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Abstract Quantifying change in ocean biology using satellites is a major scientific objective. We document trends globally for the period 1998-2012 by integrating three diverse methodologies: ocean color data from multiple satellites, bias correction methods based on in situ data, and data assimilation to provide a consistent and complete global representation free of sampling biases. The results indicated no significant trend in global pelagic ocean chlorophyll over the 15 year data record. These results were consistent with previous findings that were based on the first 6 years and first 10 years of the SeaWiFS mission. However, all of the Northern Hemisphere basins (north of 10° latitude), as well as the Equatorial Indian basin, exhibited significant declines in chlorophyll. Trend maps showed the local trends and their change in percent per year. These trend maps were compared with several other previous efforts using only a single sensor (SeaWiFS) and more limited time series, showing remarkable consistency. These results suggested the present effort provides a path forward to quantifying global ocean trends using multiple satellite missions, which is essential if we are to understand the state, variability, and possible changes in the global oceans over longer time scales.

1. Introduction

The state of ocean biology, represented by chlorophyll and observed globally by ocean color sensors, is an important indicator of climate change. Although there have been several efforts to document changes in global ocean chlorophyll observed by satellite, most are limited to a single sensor (Gregg et al., 2005; Behrenfeld et al., 2006; Henson et al., 2010; Vantrepotte and Melin, 2009; 2011; Beaulieu et al., 2013; Siegel et al., 2013). Observing climate change requires

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multiple successive missions, since the operational lifetime of any sensor is finite (typically <15 years). There are fewer efforts attempting to document historical changes globally across two missions (Gregg and Conkright, 2002; Gregg et al., 2003; Antoine et al., 2005; Martinez et al., 2009). This is a much greater challenge, because all of the ocean color missions flown to date differ greatly in radiometry, orbit, and sampling. Yet it is this challenge that must be met if we are to successfully observe climate change using satellite sensors.

The challenge of a reliable ocean color record from multiple satellites derives largely from differences in mission design. Achieving new improved observations with new and different sensors while at the same time attempting to document climate change is a very difficult undertaking, especially considering the level of consistency that is required to identify the very small changes associated with climate change on decadal time scales. Competition between building new, improved satellite sensors and continuing older designs emphasizing consistency has been won typically in favor of the new. Identical, or even similar, ocean color sensors are almost non-existent in the historical record.

Inconsistent results have affected the two modern ocean color missions, the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and the Moderate Resolution Imaging Spectrometer (MODIS) of the Aqua spacecraft. We are fortunate to have overlapping observations, enabling us to distinguish sensor-related changes from natural variability.

These inconsistencies are due to two main reasons:

- 1) different ocean color sensors observe chlorophyll distributions differently
- 2) different ocean color sensors observe different chlorophyll distributions.

Furthermore none of the missions is capable of observing truly global chlorophyll due to limitation imposed by surface obscuring features (clouds and aerosols), inter-orbit gaps, and sunlight.

1.1 Different ocean color sensors observe chlorophyll distributions differently

Differences in sensor design and orbit cause each sensor to report different values of chlorophyll even at the same location. This is despite concerted attempts to equalize the processing of the different sensor data sets. In the case of SeaWiFS and MODIS-Aqua, these sensor design differences include different band locations (MODIS has only 3 bands used for chlorophyll retrieval while SeaWiFS has 4, and some are in different spectral locations), band widths (MODIS is narrower), sensitivities (MODIS has higher digitization and signal-to-noise

ratios). The orbit differences produce viewing at different time of day (MODIS near 1330 ascending node and SeaWiFS near noon descending node but drifting in the later years). These four sensor design and orbit differences each contribute to the differences in retrieved chlorophyll, the relative contributions of which change with location and time.

1.2 Different ocean color sensors observe different chlorophyll distributions

Additionally, differences in orbit and radiance thresholds lead to the observation of different locations (Gregg and Casey 2007a). These sampling differences can be caused by sun glint, sensor tilt, solar zenith angle, inter-orbit gaps, clouds, and aerosols. Of these, solar zenith angle and aerosols are responsible for most of the sampling differences between SeaWiFS and MODIS-Aqua. The solar zenith angle limit is primarily responsible for the differences in the North Atlantic and Antarctic, and partially the North Pacific. Differences in sampling due to different masking of aerosols are the primary cause of sampling issues in the Equatorial basins and partially the North Pacific.

2. Methods

Our approach addresses the two general sources of inconsistencies between/among ocean color sensors: 1) sensor design and orbit differences resulting in different estimates of chlorophyll at the same locations and 2) sampling differences. The approach does not require knowledge of the specific errors/differences producing these generalized behaviors. For example, it does not require knowledge that out-of-band responses or electronic crosstalk in one sensor differed from another. Or that band sensitivities differed causing different masking of high aerosol optical thicknesses, resulting in sampling differences.

2.1 Empirical Satellite Radiance-In situ Data (ESRID) Approach

The Empirical Satellite Radiance-In situ Data (ESRID) approach uses relationships between satellite water-leaving radiances and in situ data after full processing, i.e., at Level-3, to improve estimates of surface variables while relaxing requirements on post-launch radiometric re-calibration (Gregg et al., 2009). The results suggest that ESRID 1) reduces the bias of ocean chlorophyll estimates, 2) modestly improves the uncertainty, 3) reduces the sensitivity of global annual median chlorophyll to changes in radiometric re-calibration, and 4) most importantly here, reduces the differences between sensor data sets (Gregg and Casey, 2010). It improves the

quality, reliability, and consistency of ocean color data, while promoting a unified description of ocean biology from satellite and in situ platforms.

ESRID applies the standard processing bio-optical algorithm after processing completion, using satellite water-leaving radiances, and in situ chlorophyll (chl)

$$\log \text{chl} = a_0 + a_1 R + a_2 R^2 + a_3 R^3 + a_4 R^4 \quad (1)$$

$$R(\lambda) = \rho(\lambda_1)/\rho(\lambda_2) \quad (2)$$

where R is the reflectance ratio, ρ is the water-leaving reflectance at a specific wavelength λ , and a_0 - a_4 are empirical coefficients. The empirical coefficients absorb biases in the radiances, most notably radiometric calibration but many others, including band location, and most out-of-band and electronic crosstalk errors. This reduces bias in the derived chlorophyll values. The empirical coefficients for SeaWiFS and MODIS-Aqua are available in Table 1.

We developed and evaluated ESRID using the latest versions of data produced by NASA and global in situ fluorometric chlorophyll data collected from the National Oceanographic Data Center (NODC; Conkright et al., 2002), NASA in situ (Werdell and Bailey, 2005), and Atlantic Meridional Transect (Aiken et al., 2000) archives, that were quality controlled (Gregg et al., 2009). We find that the SeaWiFS 2010 version produced a satellite-weighted bias (see Gregg et al., 2009) of 13.8% ($n=3531$) while MODIS version 2013 produced 5.9% ($n=1757$). After application of ESRID the results were -4.7% ($n=3154$) for SeaWiFS and -1.4% ($n=1520$) for MODIS. Uncertainties, as represented by the Semi-Interquartile Range (SIQR), were essentially unchanged and are not shown. The superior comparison between MODIS and in situ data relative to SeaWiFS is reflected in lower empirical coefficients shown in Table 1.

2.2 Data Assimilation

Our solution to sampling issues is to utilize data assimilation. This solution is general in nature and thus does not require knowledge of the specific nature of the cause and extent of the sampling errors. It starts with the ESRID bias-corrected, in situ unified data. We assimilate daily chlorophyll data from the ESRID-SeaWiFS and ESRID-MODIS using an established method (Gregg 2008).

In our data assimilation application here, we first identify regions where aerosol optical thicknesses (τ_a) are high, derived from independent sensors (Advanced Very High Resolution Radiometer Pathfinder aerosols for SeaWiFS prior to MODIS availability, and MODIS aerosols when available). We remove all ocean chlorophyll where $\tau_a > 0.25$. This is a strict limit, but we will be using nearby data points, a model, and data assimilation of uncontaminated data to fill the gaps. We prefer to err on the side of caution regarding satellite data quality and known issues associated with aerosols. Sampling differences due to aerosols and also tropical riverine influences are so large and persistent in the Equatorial Atlantic that we set our threshold in this basin to $\tau_a = 0.10$, meaning that satellite chlorophyll data where aerosols are greater than this value are removed.

Additionally, we weight model and data to remove residual anomalies from satellite data noise. This is common especially in the daily data, which is what we assimilate here. Globally, we use a model weight of 0.1. This means that at each assimilation event (model midnight), each data value is adjusted as 0.1 model and 0.9 satellite data. The borders of the model domain can contain noise deriving from coastal influences, so here we set the model weight to 0.75. In selected regions, such as the North Indian, eastern North Central (offshore Mauritania), and Okhotsk Sea, we use a variable regional weight dependent on month and satellite chlorophyll value. This is required because anomalous data make their way into the data assimilation despite the bias-correction of ESRID and the aerosol exclusions. They are typically very high, isolated chlorophyll values that are residual aerosol-contamination in the North Indian and offshore Mauritania, that set in motion extremely high phytoplankton growth in the model, eventually exceeding the capability of the available nutrients and physics to support. This results in negative nutrient values and/or excessively low dissolved inorganic carbon. In the Okhotsk Sea the result is the same but the cause is uncorrected ice in the satellite data. Tests show that regional weighting make no difference in the trend results, as the occurrences of regional issues, especially the special cases, are rare and do not affect the central tendency as represented by the median. The correction is important to maintain a high quality assimilated data set free of erroneous negative values, which occur rarely and ephemerally.

Sampling issues propagate all the way to the annual representations of global chlorophyll (Figure 1). Missing data in local winter months adversely affect the estimates of global annual median chlorophyll for ESRID-MODIS. Note the plumes of high chlorophyll in the Southern

Oceans that represent only 2 months or fewer observations, producing a skewed estimate of the global annual median. This is corrected by the 12 complete months of data in the data assimilation. We have recently introduced multi-variate data assimilation (Rousseaux and Gregg, 2012), which modifies nutrient field to retain molar ratios with chlorophyll after chlorophyll data assimilation.

2.3 Global Three-Dimensional Circulation Model

Global ocean biogeochemical dynamics for the underlying model are simulated by the NASA Ocean Biogeochemical Model (NOBM). It is a three-dimensional representation of coupled circulation/ biogeochemical/radiative processes in the global oceans (Gregg and Casey, 2007b). It spans the domain from -84° to 72° latitude in increments of 1.25° longitude by $2/3^{\circ}$ latitude, including only open ocean areas, where bottom depth $> 200\text{m}$. The biogeochemical processes model contains 4 phytoplankton groups, 4 nutrient groups, a single herbivore group, and 3 detrital pools. The phytoplankton groups (diatoms, chlorophytes, cyanobacteria, and coccolithophores) differ in maximum growth rates, sinking rates, nutrient requirements, and optical properties. The 4 nutrients are nitrate, regenerated ammonium, silica to regulate diatom growth, and iron. Three detrital pools provide for storage of organic material, sinking, and eventual remineralization. Note that because of the limitations of the model this analysis is for the open (pelagic) ocean only.

The model is spun up from prescribed initial conditions (Gregg and Casey 2007b) in free-run mode (not assimilated) for 35 years using climatological forcing from Modern-Era Retrospective analysis for Research and Applications (MERRA; Rienecker et al., 2011). It is then run with climatological forcing and data assimilation using climatological ESRID-MODIS chlorophyll for an additional 65 years for a 100-year total simulation. Very minor drift in nutrient concentrations (not chlorophyll) continue to be present, and we find a 15-year segment with the smallest change for all three nutrients (nitrate, silicate, and dissolved iron), which is $0.19\% \text{ y}^{-1}$ (mean) beginning in simulation year 77. We begin our transient run using these conditions for September 1997, the first year and month of SeaWiFS data collection. We run forward from this time until 2012 using transient forcing from MERRA, switching from ESRID-SeaWiFS to ESRID-MODIS in January 2003.

Statistical Treatment of Trends

We derive trends using linear regression analysis on annual median chlorophyll data from the ESRID-assimilation. The sequence involves computation of 1) monthly mean values at each grid point from daily assimilation model outputs, 2) the median of the 12 monthly means of each year to remove the seasonal signal at each grid point, 3) for the global and basin analysis, annual median chlorophyll spatially as a representation of the central tendency, acknowledging the non-Gaussian distribution of global ocean chlorophyll (Campbell, 1995), 4) best-fit linear trends, and 5) statistical significance of the trends (Zar, 1976). Trend maps are produced omitting step 3. A statistically significant trend is one that exceeds the 95% confidence level. This is a time-first, space-second derivation of the annual central tendency. We recognize that the use of annual medians reduces our sample number and thus increases our chances of Type-II errors (not detecting a trend when one exists), but we prefer to err in this direction rather than in the direction of a Type-I error (falsely detecting a trend when one does not exist).

The 15-year time series of chlorophyll represents 13 degrees of freedom for regression analysis. As a relatively short time series, it is prone to end point bias, which can occur when the first or last points of the time series are exceptionally high or low relative to the series as a whole. Such anomalous end points can drive the regression analysis to an artificial representation of a trend and its statistical significance. We reduce this issue by removing the first or last annual median value if it is the highest or lowest of the entire series. The approach is conditional in that if removal of end points creates a new trend that did not previously exist, we revert to the original series (retaining the original end points). We do not perform end point removal recursively, as this can lead to absurd results (for example, a perfectly straight line, i.e., perfect trend, would be eliminated). This reduces our degrees of freedom and the probability of finding significant trends. Degrees of freedom are indicated on trend figures. Like the use of medians and annual values, this is a conservative approach to minimize the chances of detecting trends when they do not exist.

The end point bias reduction procedure does not affect the detection of significant trends globally or in the basin analyses. It does change the value of the trend, however, and in every case it produces a smaller estimated trend. For the trend maps, the end-point bias correction reduces the number of significant trends modestly. Trends in chlorophyll are reported as percent, computed from the linear trend, with the chlorophyll value at the y-intercept representing the starting point.

3. Results

Uncorrected SeaWiFS (1998-2007) and MODIS-Aqua (2003-2012) global annual median chlorophyll each show no significant trend at the 95% confidence level (Figure 2). We ignore SeaWiFS data for 2008 and 2009 because of severe sensor issues that caused significant loss of data (discussed later) resulting in a poorly defined annual median. When we switch from SeaWiFS to MODIS in 2003, we obtain a significant decreasing trend ($P < 0.02$), due to the differences in global annual median chlorophyll reported by MODIS and SeaWiFS. This significant declining trend occurs whether we switch in 2003 or any year through 2007. The correlation coefficient ranges from -0.654 in the 2003 switch to -0.692 in the 2007 switch, and there is no change in the probability.

Using our new ESRID-assimilated data, again with the sensor switch in 2003, we do not observe a significant change in the new 15-year time series (Figure 3). We note that the last data point for 2012 in the time series was removed because it was the lowest chlorophyll annual median recorded and thus could potentially contribute to end point bias. In our adjusted time series we derive a correlation coefficient of -0.254.

When we refine our analysis to basin scales, we observe significant trends in 6 of the 12 major oceanographic basins (Figure 4). They are overwhelmingly northern basins with the addition of the Equatorial Indian Ocean. Trend statistics for the basins with significant trends and their probabilities show that, in every basin, the correlation coefficients are negative indicating a decline in annual median chlorophyll (Figure 5).

A trend map allows us to focus on locations driving the basin scale trends in annual median chlorophyll. It also allows us to observe areas with trends that do not aggregate to the basin scale (Figure 6). Widespread negative significant correlations predominate in the northern hemisphere, corresponding to the basin scale results. In fact, there are only small isolated regions exhibiting positive trends, such as offshore the US west coast and the Davis Strait north of the Labrador Sea.

The Southern Hemisphere, conversely, has large regions of positive significant trends, sprinkled among locations with negative trends (Figure 6). Particularly noteworthy is the positive trend offshore of the Patagonian shelf, extending nearly across the southern South Atlantic basin. Other positive trends are observed in the Tasman Sea and south, eastern South

Pacific, and the northern Weddell Sea (Figure 6). The central South Pacific exhibits a strong region of significant decline in annual median chlorophyll. The upwelling zone of the tropical Pacific also shows a strong decline.

4. Discussion

The present work continues and extends efforts by others (Gregg et al., 2005; Henson et al., 2010; Vantrepotte and Melin, 2009; 2011; Beaulieu et al., 2013; Siegel et al., 2013) to identify and document global trends in the modern ocean color record, beginning in 1997 with SeaWiFS. It extends the previous efforts by 1) using a new, consistent multi-sensor combination, 2) removing sampling biases using data assimilation, and 3) providing additional data and establishing a 15-year time series. Previous efforts have all utilized SeaWiFS only and have been limited by the sampling of that sensor, unlike the present effort that eliminates sampling biases using data assimilation. Gregg and Casey (2007a) have established the importance and distributions of biases associated with satellite missions, noting that they are especially important in the presence of persistent clouds and aerosols, and in the high latitudes.

Only two of the previous efforts (Gregg et al., 2005; Beaulieu et al., 2013) have reported global trends. We report here that their findings of no significant trend in the global open (pelagic) ocean for the period 1998-2003 (Gregg et al., 2005) continues through 2007 (Beaulieu et al., 2013) and through 2012 in this study. Although global annual median chlorophyll is lower at the end of the record than at the beginning, the trend is not as large as the interannual variability, which precludes its characterization as significant ($P < 0.05$). Our conservative approach further inhibits the ability to detect a trend, which, as noted in the methods, we consider a desirable characteristic.

We find here that global data subdivided into the 12 major oceanographic basins show significant declines for all Northern Hemisphere basins and additionally the Equatorial Indian (Figures 2 and 3). Beaulieu et al. (2013) found a significant decline for the North Atlantic but not for the other basins above. We attribute this to our extended data record length (5 additional years). This enables the present time series to encompass more of the new Pacific Decadal Oscillation phase, a pattern of decadal variability that affects the North and North Central Pacific. Additionally, the improved sampling and aerosol exclusion in our analysis may contribute to the differences. Our finding of significant declines in the North and Equatorial

Indian basins is also not reported by Beaulieu et al. (2013) and may be due to our aerosol exclusion, in addition to our extended time series. Contributions by decadal variability cannot be discounted either.

Although global trends have only been sparsely reported in the literature, trend maps have been produced by four of the aforementioned previous efforts (Gregg et al., 2005; Henson et al., 2010; Vantrepotte and Melin, 2011; Siegel et al., 2013). Here we summarize the record to document trends in ocean chlorophyll observed from space and attempt to identify the causes. We are interested here in the causes arising from methodological and data records, as opposed to relationships with temperature (Gregg et al., 2005; Behrenfeld et al., 2006; Vantrepotte and Melin, 2009; Siegel et al., 2013), surface data (Gregg et al., 2005), and climate variability indices (Vantrepotte and Melin, 2011), which have been established.

The five observational efforts have used different approaches, and mostly represent trends over different time periods (Table 2). All except the present effort began with monthly mean chlorophyll data at 9km spatial resolution. Gregg et al., (2005), Henson et al., (2010), and Siegel et al., (2013) essentially used the same methodology of monthly anomalies, although Gregg et al. (2005) aggregated the monthly anomalies into annual anomalies and Siegel et al. (2013) used a logarithmic transformation. Offline tests using annual means as in Gregg et al. (2005) instead of annual medians show minor differences in the trend maps, a finding that applies to the logarithmic transformation as well. Thus the efforts by Gregg et al. (2005), Henson et al. (2010), and Siegel et al. (2013) can be considered similar approaches with different analysis time periods. Vantrepotte and Melin (2011) overlapped time periods with Henson et al. (2010), but used a very different approach, including gap filling using principal components analysis and trend analysis using the Census X-11 methodology.

Perhaps the most striking observation is the similarity of trends observed by the five different efforts (Figure 7). Specifically, the significant declines in the middle North Central Atlantic, central South Pacific and Indian, Bay of Bengal, and west-central South Atlantic are common to all the analyses. Similarly, significant increases offshore of the Patagonian shelf, eastern South Pacific and Atlantic, the extreme western Equatorial Pacific, and the US west coast are observed by all five representations (Figure 7). This suggests that, considering the analysis of different time periods, there appear to be persistent changes in the biology of the global oceans. It also suggests that despite different processing versions, calibration and sensor issues, methodologies

and sensors, we are able to detect similar patterns of moderate-term changes in the oceans using spaceborne sensors. This gives us confidence in our observational systems and the handling of data by the processing teams.

There are major differences as well. Some appear to be new occurrences. For example, significant increases have occurred in the Tasman Sea in all 4 of the more recent observations that were not apparent in the 1998-2003 record (Figure 7). A patch of declining chlorophyll in the central Equatorial Indian in the 1998-2003 time period disappeared by 2007, and instead a region appeared to the southeast, closer to Australia. This was apparent in the 2010 observations but more to the west, as it also appears in the 2012 observations.

Unique trends in the present extended effort are apparent. Some are due to the treatment of the data here (Table 2). Some are due to changes in the record. These may represent longer term changes or shorter term variability such as decadal variability which is now captured by the longer time series. Significant increases documented in the South Australian Basin in the 1998-2003, 1997-2007, and 1997-2010 are now missing in the longer time record. Widespread increases in chlorophyll in the Southern Oceans in the 1998-2012 observations generally contrast with scattered declines in the 1998-2003 time period. However, there appears to be an increase in the positive trends here in 1997-2010, and the basin as a whole was found to be significantly increasing by Siegel et al. (2013). It is not statistically increasing as a basin in the present analysis. There are also more abundant positive trends here in the Henson et al. (2010) version of the 1997-2007 trends, suggesting a change is occurring.

The region of steeply declining chlorophyll due south of Iceland intensified between the 1998-2003 and 1997-2010 records, but has retreated westward and receded in the most recent trends. Analysis of the MODIS portion of the record using ESRID-assimilation (data not shown) shows a reversal in trend in the portion closest to the United Kingdom, suggesting changes in the more recent part of the record.

In our recent analyses, the entire North and Equatorial Indian basins exhibit negative trends (Figure 7). Although the Bay of Bengal decline is persistent in the previous analyses, the Arabian Sea decline is new to the 1998-2012 results. In addition to new declines, previously reported increases along the Somali coast and extending seaward have disappeared. We note it is vastly diminished in the 1997-2010 time series analysis. It is possible the pre-2010 efforts exhibit artifacts due to aerosols, which are prevalent here and which complicate trend analysis by

1) mimicking chlorophyll when they are not masked and 2) create biases in sampling when they are masked. Both effects change seasonally and interannually. Removal of satellite data where $\tau_a > 0.25$ reduces the chances of aerosol trends and non-uniform masking affecting the chlorophyll trends.

Also notable in the new multi-mission trend analysis is the near absence of positive trends in the northern high latitudes (Figure 7). Slivers of positive trends in the 1997-2007 and 2010 representation appear to be associated with the sub-polar Pacific frontal zone, which may suggest a spatial shift more than a local trend. The high latitudes are problematic for satellite sampling, with major portions of the year missing due to insufficient light availability for reliable surface retrieval. Even when sufficient light is available, persistent cloud cover in these regions can produce severe biases in the representation of chlorophyll distributions here (Gregg and Casey, 2007a). The North Pacific has the additional handicap of aerosol obscuration in the springtime from the Mongolian desert, which further complicates the analysis of trends. Our aerosol-exclusion/data assimilation approach resolves these sampling issues and provides a more reliable estimate of trends here.

Finally, the present 1998-2012 trend analysis shows a modest but significant decline in chlorophyll in the eastern Equatorial Pacific (Figure 7). None of the time series analyses ending at or later than 2007 analyses exhibit this feature, although hints of it may be seen in all of them. It is apparent in the 1998-2003 analysis but is less pronounced. Tests using annual medians of the sensor data sets show its appearance in SeaWiFS from 1998-2007 and also in the MODIS 2003-2012 time series (data not shown), suggesting that it is a continuation and enhancement of a trend over the 1998-2012 record that is accentuated by our choice of annual trend analysis, and is not seen prominently in the monthly anomaly results. This is likely the result of El Niño-Southern Oscillation patterns, more of which are captured in our extended time series with MODIS.

Our analysis is new in that we use a multi-mission capability instead of the previous single sensor analyses. Since there is much understanding associated with the first modern mission, SeaWiFS, and far more research than on the newer mission, MODIS, it is reasonable to ask why we chose to discontinue use of SeaWiFS as soon as the first full year of MODIS became available. Our reasoning is the superiority of MODIS in comparison with in situ data, its improved signal, its stable orbit, and its reduced noise suggest it is a superior sensor that we

would want to utilize as soon as it is available. We recognize its stability issues, but the similarity of many of our results with single-sensor results suggests its robustness. We further note that the last 3 years of SeaWiFS are of dubious quality. In 2008 and 2009 mission issues limited SeaWiFS to 217 and 223 observation days, respectively, representing only 60% of the data from previous years. Before that, no more than 5 days were missing in any year. MODIS has no missing days from 2003 through 2012. Additionally, major changes in nodal drift occurred for SeaWiFS (Meister et al., 2012). Its equator crossing time drifted nearly 2 hours by 2010. It was slightly <0.5 h in 2005 and ~ 45 min in 2007. This means it viewed a different growth status of phytoplankton as it aged. Additionally, it viewed a different portion of the oceans, especially the high latitudes, over time. SeaWiFS' nodal drift diminished coverage in the extreme high latitudes as it drifted, but its descending node reduced the northern oceans more. These issues occur at the end of the mission, giving them more weight in trend analysis than if they had occurred toward the middle of the time series. These late mission issues complicate trend analysis using SeaWiFS after 2007.

The global trends constructed here are for a 15 year period of global satellite observations from modern capability satellite missions, in situ bias correction, and data assimilation. This period is insufficient to rule out variability rather than climate change. We are cognizant of the much longer records needed to unambiguously identify change (Henson et al., 2010). However, it is important to catalog the trends as they occur from these modern scientific tools to improve our understanding of the state of ocean biology and how it is changing. We make no inference about the future but strictly report on the observed trends for 15 years based on a careful analysis.

Our approach to the understanding of global trends emphasizes conservatism: we use annual medians, rather than monthly, and we remove possible false trends associated with trend end points. This limits our ability to detect trends, but it is intentional. It improves the reliability of our results and decreases the uncertainty that the trends found are genuine. We are encouraged at the similarities in findings among the approaches, at the same time the differences, and expect that the combination of different approaches can yield in the aggregate improved understanding of ocean biological processes.

Analysis of global trends in ocean chlorophyll is sensitive to the radiometric stability of the observing platforms. This is not an exact science, but use of extraterrestrial radiometric sources (sun and/or moon) provides a measure of independence necessary to achieve some level of

confidence. MODIS-Aqua used lunar and solar observations for stability correction through 2007, and then normalization of radiometric stability to SeaWiFS (Meister et al., 2012). Since the demise of SeaWiFS in 2010, calibration scientists have struggled with understanding MODIS stability, resorting to Earth targets, which carry unknown trend uncertainty. The most recent two years of the mission data set were re-evaluated twice in 2013, with nearly all of the changes in chlorophyll appearing in 2013. There is no absolute reference for radiometric stability and it is a potential contributor to the uncertainty of any trend analysis using satellite data. We note that the last year of our time series 2012 was the lowest median globally and for some basins. However, the 2013 global median is much higher and is within 0.04% of the mean of the MODIS data record and 0.1% of the median. This observation, plus the similarities we observe in this effort with previous efforts suggest confidence that the observed trends are likely larger than unknown stability issues for the SeaWiFS and MODIS data sets. We also recognize that uncorrected radiometric stability has the potential to affect the trends reported here, but it is important to proceed with estimating global trends assuming best efforts by mission teams to remove or reduce these instabilities.

Summary

A new integration of information from in situ data and data assimilation models closes the disparities in chlorophyll from different ocean color satellites and permits the use of multiple satellites to observe decadal trends. Using this new integrated assessment, we find that there is no trend in global chlorophyll over the 15-year period 1998-2012. However, there are basin scale and local trends significant at a probability of 95% ($P < 0.05$). The entire Northern Hemisphere ocean basins and the tropical Indian basin exhibit significantly declining trends. On local scales positive and negative trends are apparent and show agreement with previous efforts over shorter time domains and using a single sensor. This finding gives us confidence that our new multi-satellite approach enhanced with information from in situ data and models via data assimilation produces realistic trend information over decadal time scales. Possibly more important, our data/model integration methodology suggests a path forward for continuing the observation of global and regional trends in chlorophyll into the future, as satellite missions are replaced with new ones, typically with different sensors and orbits.

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References

- Aiken, J., and 6 others, 2000. The Atlantic Meridional Transect: Overview and synthesis of data. *Progress in Oceanography* 45: 257–312.
- Antoine, D., Morel, A., Gordon, H.R., Banzon, V.F., and Evans, R.H., 2005. Bridging ocean color observations of the 1980s and 2000s in search of long-term trends. *Journal of Geophysical Research* 110: C06009, doi:10.1029/2004JC002620.
- Beaulieu, C., Henson, S.A., Sarmiento, J.L., Dunne, J.P., Doney, S.C., Rykaczewski, R.R., and Bopp, L., 2013. Factors challenging our ability to detect long-term trends in ocean chlorophyll. *Biogeosciences* 10: 2711-2724, doi:10.5194/bg-10-2711-2013.
- Behrenfeld, M.J., and 9 others, 2006. Climate-driven trends in contemporary ocean productivity. *Nature* 444: 752-755.
- Campbell, J.W., 1995. The lognormal distribution as a model for bio-optical variability in the sea. *Journal of Geophysical Research*, 100: 13237-13254.
- Conkright, M.E., and 10 others, 2002. World ocean database 2001, Vol. 1: Introduction. S. Levitus, Ed., NOAA Atlas NESDIS 42, US Govt. Printing Office, Washington, DC, 167 pp.
- Gregg, W.W. and M.E. Conkright, 2002. Decadal changes in global ocean chlorophyll. *Geophysical Research Letters* 29 (11): 10.1029/2002GL014689.
- Gregg, W.W., Conkright, M.E. Ginoux, P. O'Reilly, J.E. and Casey, N.W. 2003. Ocean primary production and climate: Global decadal changes. *Geophysical Research Letters* 30 (15) 1809, doi: 10.1029/2003GL016889.

- Gregg, W.W., Casey, N.W. and McClain, C.R. 2005. Recent trends in global ocean chlorophyll. *Geophysical Research Letters*, 32, L03606, doi:10.1029/2004GL021808.
- Gregg, W.W. and Casey, N.W. 2007a. Sampling biases in MODIS and SeaWiFS ocean chlorophyll data. *Remote Sensing of Environment* 111: 25-35.
- Gregg, W.W. and Casey, N.W., 2007b. Modeling coccolithophores in the global oceans. *Deep-Sea Research II* 54: 447-477.
- Gregg, W.W., 2008. Assimilation of SeaWiFS ocean chlorophyll data into a three-dimensional global ocean model. *Journal of Marine Systems* 69: 205-225.
- Gregg, W.W., Casey, N.W. O'Reilly, J.E. and Esaias, W.E. 2009. An empirical approach to ocean color data: Reducing bias and the need for post-launch radiometric re-calibration. *Remote Sensing of Environment* 113: 1598-1612.
- Gregg, W.W. and Casey, N.W. 2010. Improving the consistency of ocean color data: A step toward climate data records. *Geophysical Research Letters*, 37, L04605, doi:10.1029/2009GL041893.
- Henson, S.A., Sarmiento, J.L., Dunne, J.P., Bopp, L., Lima, I., Doney, S.C., John, J., and Beaulieu, C., 2010. Detection of anthropogenic climate change in satellite records of ocean chlorophyll and productivity. *Biogeosciences* 7: 621–640.
- Martinez, E., Antoine, D., D'Ortenzio, F., and Gentili, B., 2009. Climate-driven basin-scale decadal oscillations of oceanic phytoplankton. *Science* 326: 1253-1256.
- Meister, G., Franz, B.A., Kwiatkowska, E.J., and McClain, C.R., 2012. Corrections to the calibration of MODIS Aqua ocean color bands derived from SeaWiFS data. *IEEE transactions on Geoscience and Remote Sensing* 50: 310-319.
- Rienecker, M. M., Suarez, M.J., Gelaro, R., Todling, R., Bacmeister, J., Liu, E., Bosilovich, M.G., Schubert, S.D., Takacs, L., Kim, G.-K., Bloom, S., Chen, J., Collins, D., Conaty, A., da Silva, A., et al., 2011. MERRA - NASA's Modern-Era Retrospective Analysis for Research and Applications. *Journal of Climate* 24: 3624-3648. doi: 10.1175/JCLI-D-11-00015.1.
- Rousseaux, C.S. and Gregg, W.W., 2012. Climate variability and phytoplankton composition in the Pacific Ocean. *Journal of Geophysical Research* 117, C10006, doi:10.1029/2012JC008083
- Siegel, D.A., and 25 others, 2013. Regional to global assessments of phytoplankton dynamics

- from the SeaWiFS mission. *Remote Sensing of Environment* 135: 77-91.
- Vantrepotte, V., Melin, F., 2009. Temporal variability of 10-year global SeaWiFS time-series of phytoplankton chlorophyll a concentration. *ICES Journal of Marine Science* 66:1547–1556.
- Vantrepotte, V., Melin, F., 2011. Inter-annual variations in the SeaWiFS global chlorophyll a concentration (1997–2007). *Deep-Sea Research I* 58: 429–441.
- Werdell, P.J. and Bailey, S.W., 2005. An improved in-situ bio-optical data set for ocean color algorithm development and satellite data product validation. *Remote Sensing of Environment* 98:122-140.
- Zar, J. H. (1976), *Biostatistical Analysis*, 3rd ed., Prentice-Hall, Upper Saddle River, N. J.

Figure Captions

Figure 1. Top left: Global annual median chlorophyll from ESRID SeaWiFS for 2006. Top right: ESRID MODIS-Aqua. Bottom: Global annual median chlorophyll from the ESRID-assimilation for 2006 using MODIS-Aqua. Note the areas of high chlorophyll in ESRID SeaWiFS and MODIS data in the high latitudes that are reduced in the assimilation data. These are artifacts of sampling only the warmer, more sunlit months by the satellites while the assimilation model produces information for all days of the year. Similar reductions in global annual median assimilated chlorophyll occur in the North Indian Ocean due to seasonal aerosol obscuration.

Figure 2. Uncorrected SeaWiFS and MODIS-Aqua global annual median chlorophyll. Trends for SeaWiFS and MODIS are shown and are each not significant at the 95% probability level. A combined SeaWiFS-MODIS time series with a switch in 2003 (first full year of MODIS) shows a significant trend ($P < 0.02$; 98% confidence). The black dashed lines indicate trends using other years for the switch: 2004-2007, indicated successively higher. The correlation coefficient changes slightly but the significance and probability do not.

Figure 3. Global annual median chlorophyll. Uncorrected SeaWiFS and MODIS-Aqua trends with a switch at 2003 show a significant decline ($P < 0.02$). The ESRID-assimilated trend shows no significant trend (as both SeaWiFS and MODIS-Aqua do, individually). ESRID-assimilation

shows reduced chlorophyll reflecting in situ bias-correction and sampling bias-correction. Note the end point bias correction as indicated by the missing marker in 2012, resulting in $df=12$.

Error bars denote the Semi-Interquartile Range over the months of each year.

Figure 4. Basin definitions for the ESRID-assimilation. Basins that exhibited significant trends over the 15 year 1998-2012 period are highlighted in blue, with the trend percent per year shown.

Figure 5. Trends for the six basins that showed significant declines. Note they are all the northern hemisphere basins plus the tropical Indian Ocean. Correlation coefficients and probability levels are shown, along with the degrees of freedom (df) that ameliorates end point bias.

Figure 6. Trend map showing specific locations where significant trends in annual median chlorophyll were observed (top). Red indicates a positive trend and blue indicates a negative trend. White indicates no significant trend at $P<0.05$. Bottom: start (left) and end (right) chlorophyll concentration from the trend regression (mg m^{-3}).

Figure 7. Comparison of 5 representations of chlorophyll trend maps in units of percent per year (except middle left which is $\text{mg m}^{-3} \text{ y}^{-1}$). Figures reprinted with authors' permission.

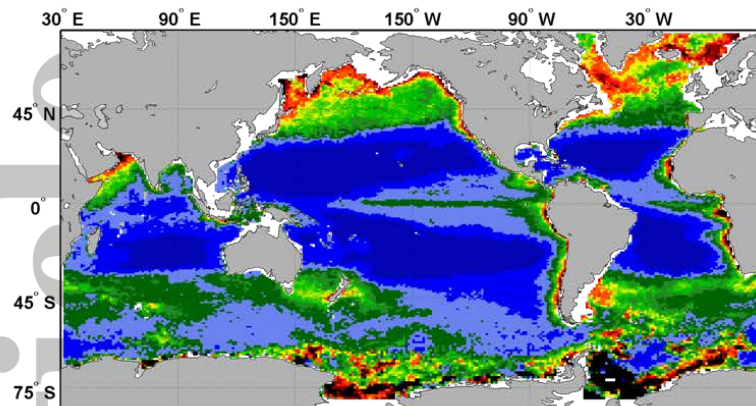
Table 1. Empirical coefficients for the pelagic oceans used for SeaWiFS and MODIS-Aqua for the bias-correction ESRID method.

Coefficients	SeaWiFS	MODIS-Aqua
ao	0.4736	0.2861
a1	-3.9267	-3.2016
a2	3.2867	2.4534
a3	0.8442	0.7877
a4	-2.9636	-2.6426

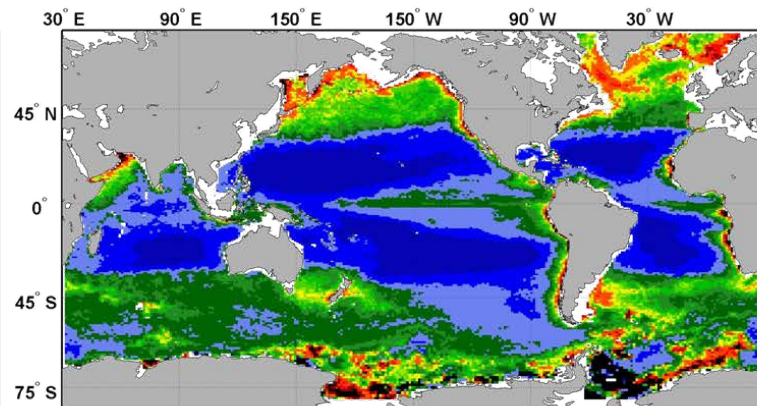
Table 2. Comparison of methodologies by previous and present efforts to produce trend maps from different sensors and time records.

Authors	Years	Sensor/ Processing Version (PV)	Initial Data	Analysis Resolution	Special treatment	Trend analysis
Gregg et al. (2005)	1998-2003	SeaWiFS PV: 2003	9km Monthly means	25km Annual mean anomalies (n=6)		Linear regression
Henson et al. (2010)	1997-2007	SeaWiFS PV: V5.2	9km Monthly means	Spatial resolution unknown Monthly mean anomalies (n=124)		Linear regression
Vantrepotte and Melin (2011)	1997-2007	SeaWiFS PV: R2009	9km Monthly means	27km at equator Monthly means (n=120)	Selective data removal, gap filling (PCA)	Census X-11
Siegel et al. (2013)	1997-2010	SeaWiFS PV: 2010	9km Monthly means	1°x1° Monthly mean anomalies (n=154)	Logarithmic transformation, treatment of detrital material	Linear regression
This effort	1998-2012	SeaWiFS 1998-2002 PV: 2010 MODIS 2003-2012 PV: 2013	1.25°x0.67° Monthly means (after bias- correction and data assimilation)	1.25°x0.67° Annual medians (n=15)	Bias correction, data assimilation, end point bias removal, medians, treatment of aerosols	Linear regression

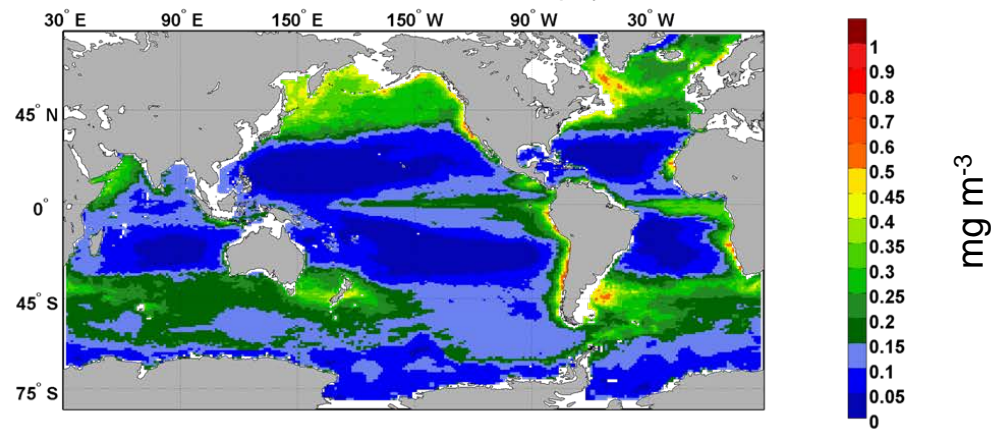
ESRID Annual Median Chlorophyll for SeaWiFS 2006

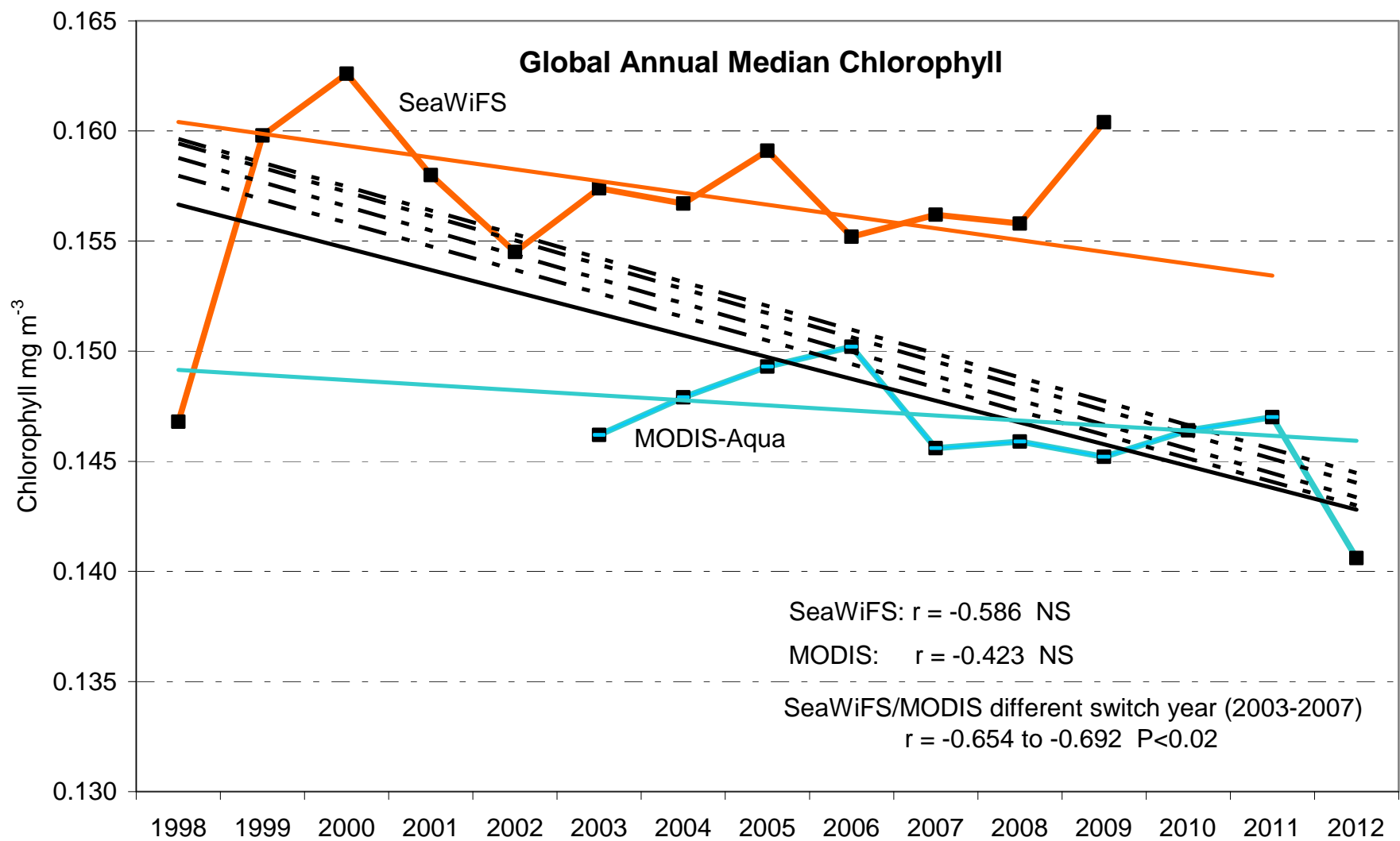


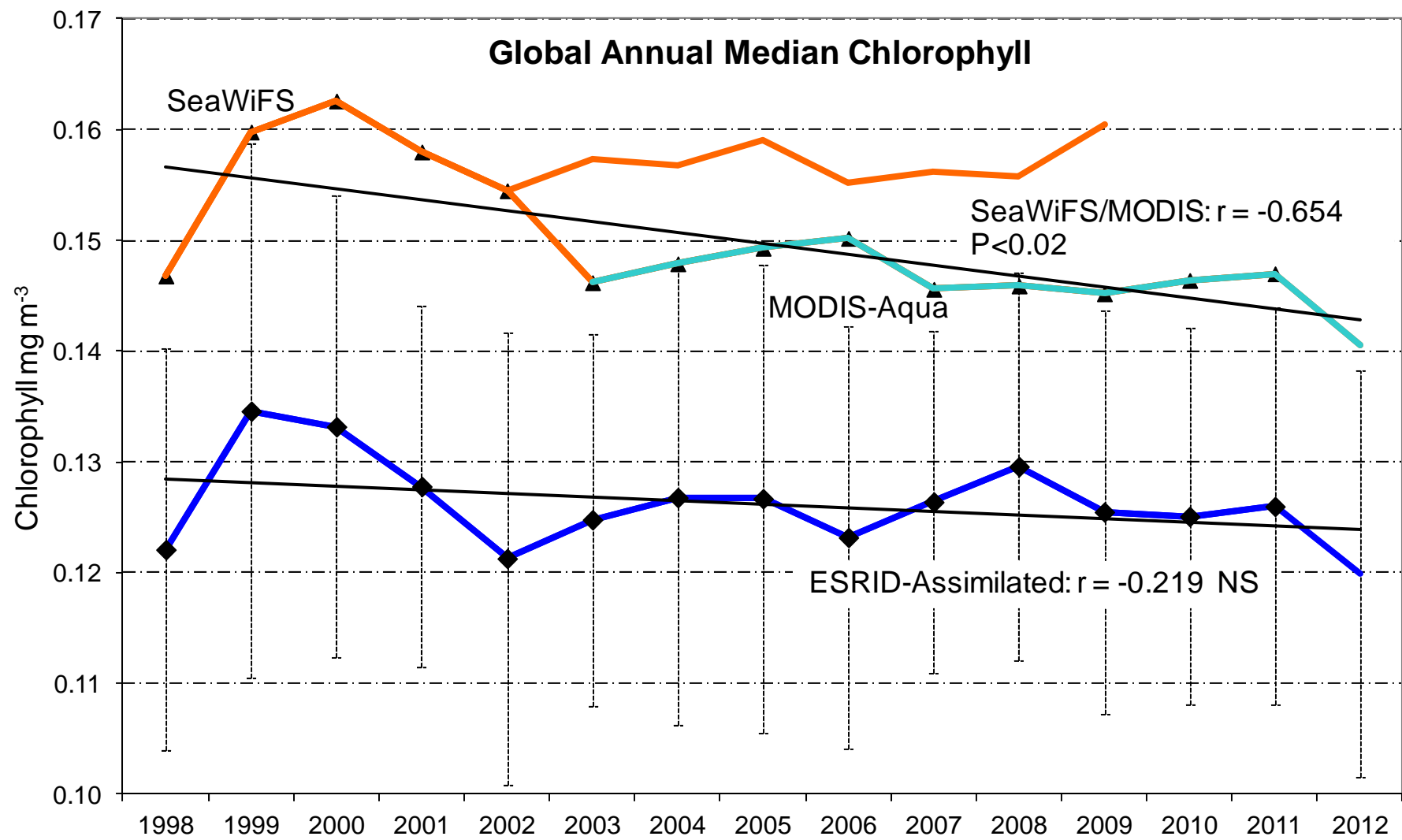
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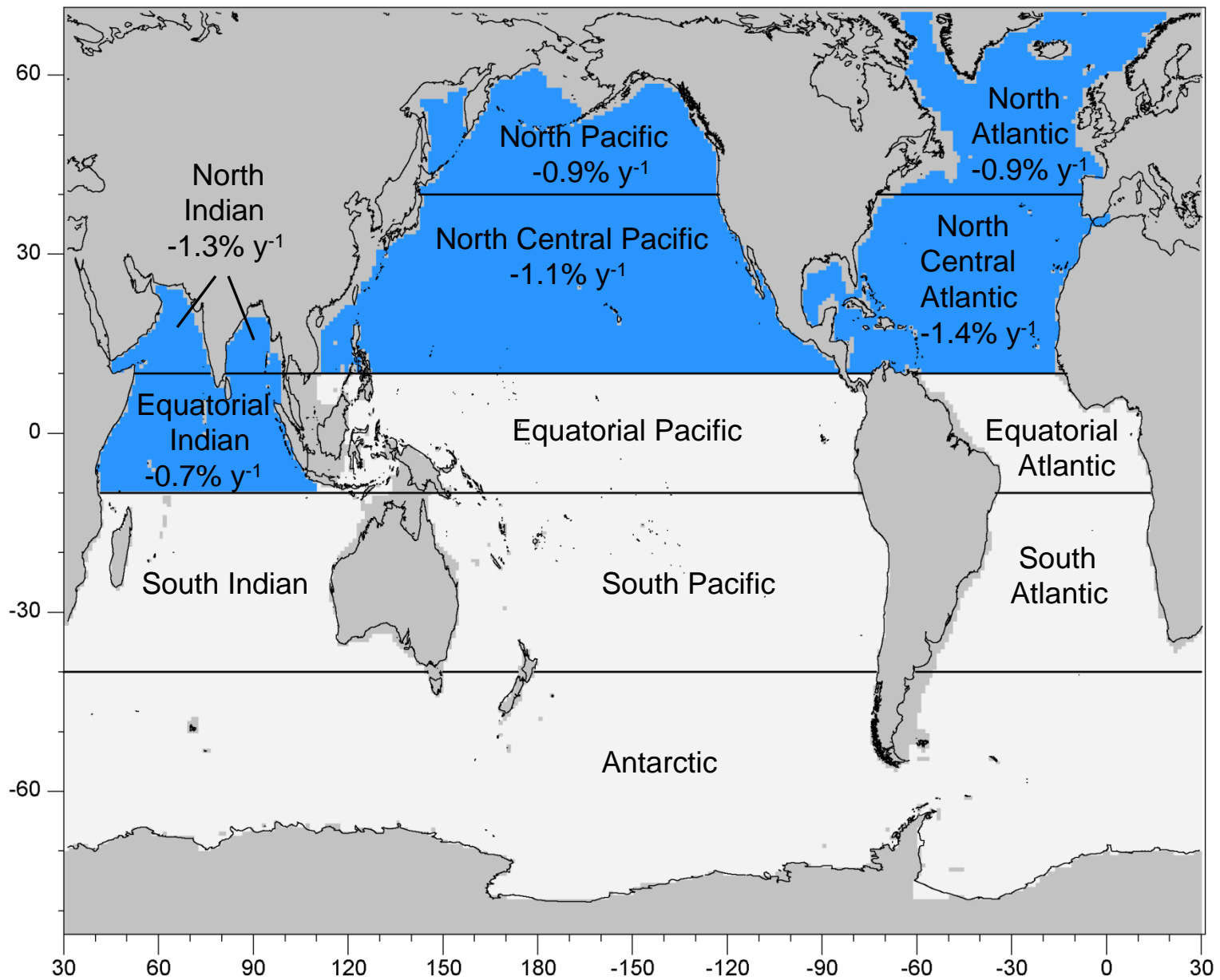


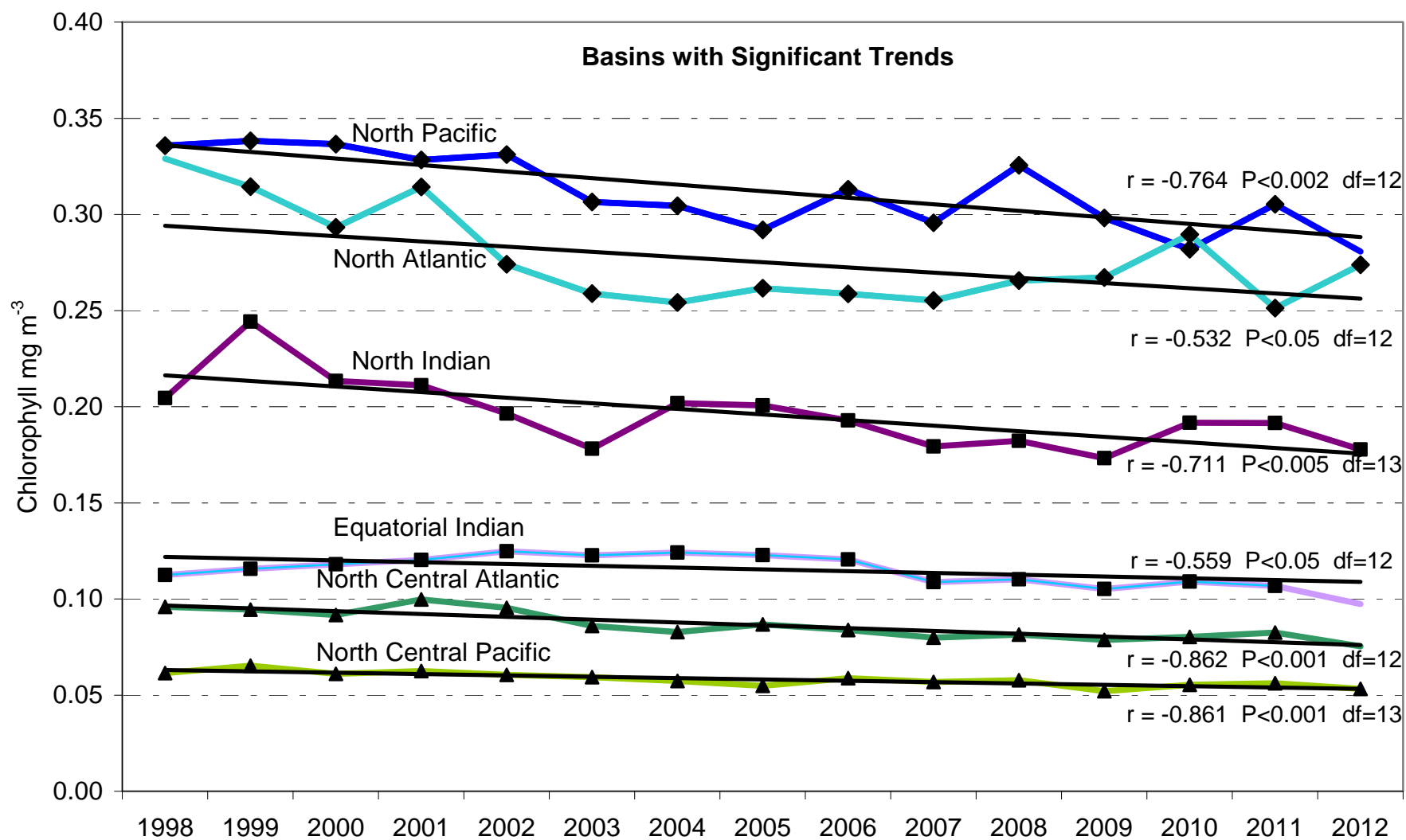
ESRID-Assimilated Annual Median Chlorophyll for MODIS 2006



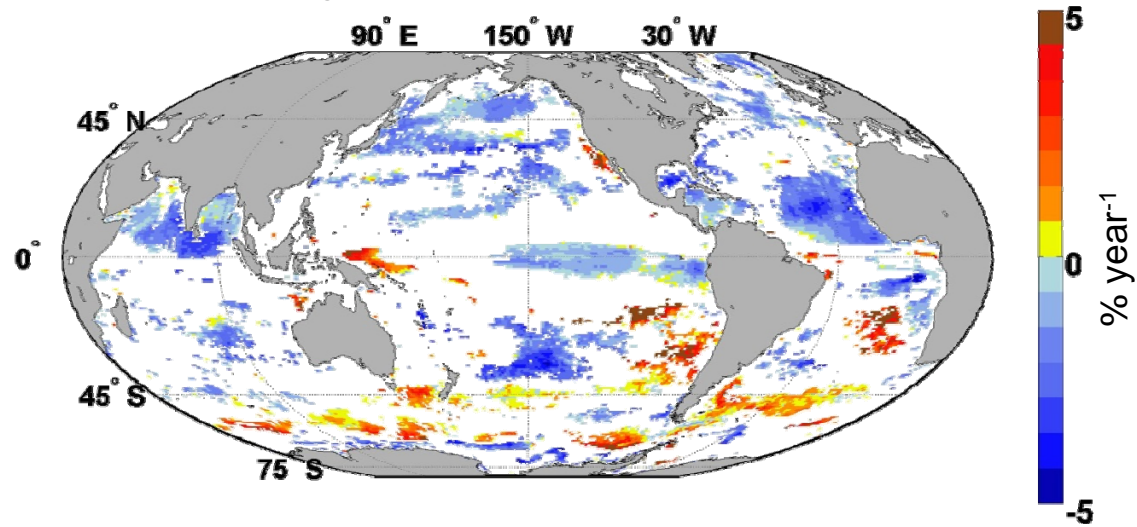




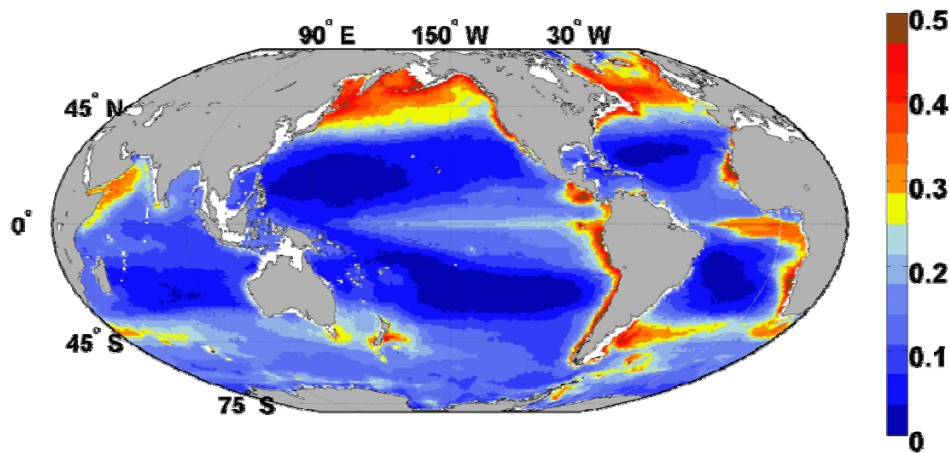




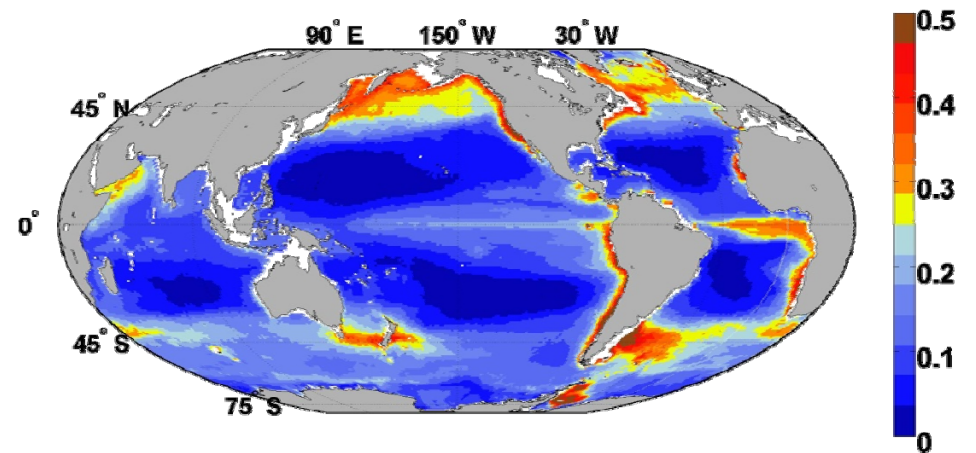
Significant Trends 1998-2012



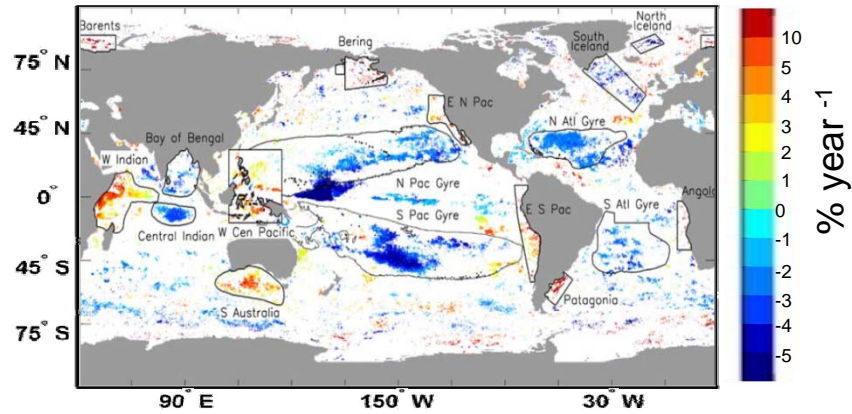
Annual Median Chlorophyll Best Fit 1998



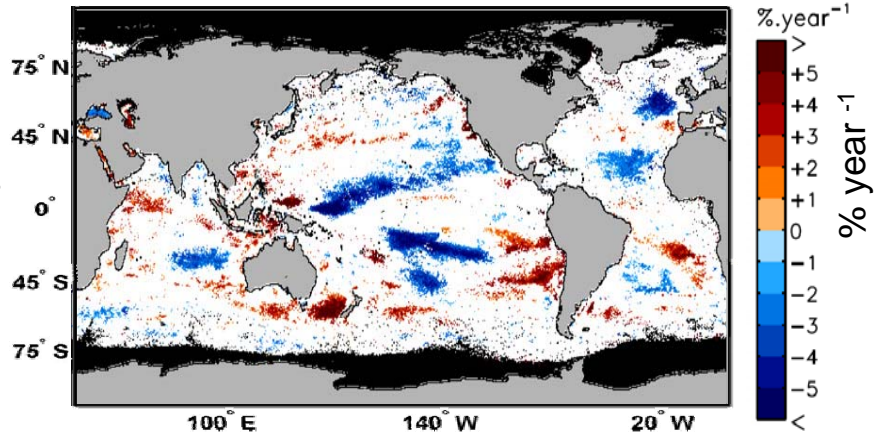
Annual Median Chlorophyll Best Fit 2012



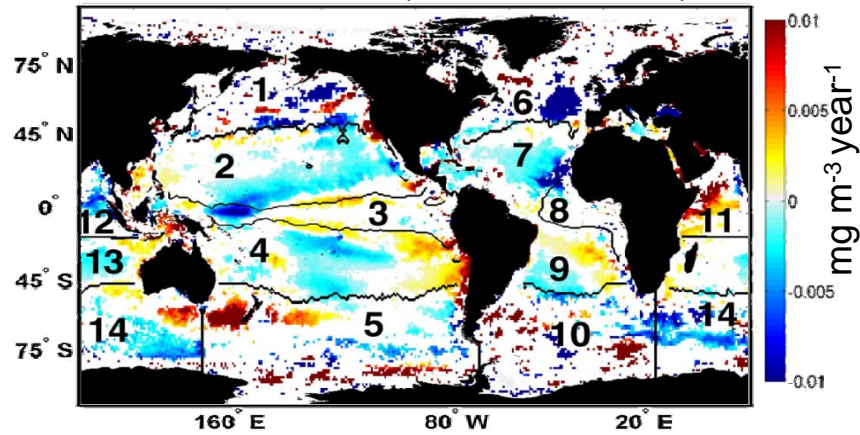
SeaWiFS 1998-2003 (Gregg et al. 2005)



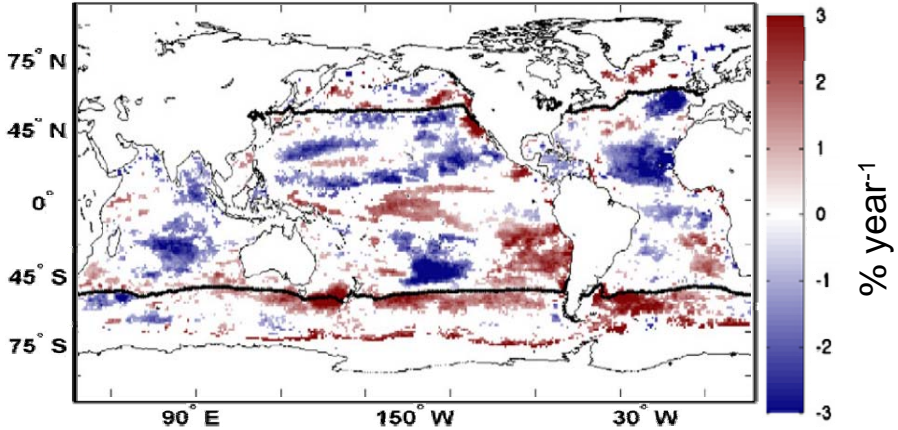
SeaWiFS 1997-2007 (Vantrepotte and Melin 2011)



SeaWiFS 1997-2007 (Henson et al. 2010)



SeaWiFS 1997-2010 (Siegel et al. 2013)



SeaWiFS-MODIS 1998-2012 (This work)

